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Tools to Evaluate Strategies for Utilization of Low Temperature Geothermal Resources

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ABSTRACT

A tool for making basic evaluations of strategies for utilization of low temperature geothermal resources has been developed. It is used to assess the profitability and lifetime of the field in light of the dynamics of the geothermal reservoir and varying production profiles. The reservoir dynamics are simulated using a simple lumped parameter model based on physical data. Production can be varied as a function of time and may include stochastic effects to mimic fluctuating market demand. We present some initial work that looks at an analog of the Lauganes geothermal field nearby Reykjavík, Iceland. We make the assumption that the provider must meet market demand, namely that if demand exceeds production for a given number of days, n, pumping capacity must be increased. This criterion is superceded by another that limits the pumping power to a given fraction of the exergy of the geothermal fluid being pumped up. Results show maps of profitability and lifetime under various operating conditions for different values of parameters such as the rate of return, number of days that demand may exceed supply, reservoir size and conductivity.

1. INTRODUCTION

Although natural geothermal systems may be considered to be renewable in the sense that their rate of depletion is of the same time scale as the rate of renewal, as discussed in Stefánsson (2000), aggressive production can lead to situations where further production is not economically viable for an extended time period. Planning is essential to strive for optimal operations that fulfill expectations of sustainability. Since perfect knowledge, of market conditions and the physical characteristics of the geothermal reservoir, is unobtainable it is necessary to take uncertainties into account in the planning process. Uncertainty about the capacity of the reservoir, market demand and prices make planning more difficult and increase the risk of the operations not meeting the required performance. However, more accurate information and modeling may prove to be quite costly to obtain and not lead to sufficient certainty about the future to justify those costs. We use a computationally cheap lumped parameter model that characterizes a low-temperature field adequately, with semi-stochastic time series describing market conditions to map out the possible production profiles for the field under various constraints on meeting customer demand and sustainability criteria.

Lumped parameter models have been applied successfully to predict pressure changes in low temperature geothermal systems, e.g Axelsson (1989), Björnsson (2005) and Sarak (2005). Their simplicity lends itself ideally to parametric surveys and examinations of stochastic behavior that call for large numbers of calculations of system response under different conditions. In this paper we present a method of carrying out such surveys and show some preliminary results obtained from them. By conducting such parametric surveys it is possible to get a feel for what parameters are most important and what regions of "parameter space" should be investigated using more accurate methods.

2. THE MODEL

2.1 Lumped Parameter Model

The lumped parameter model that we use in this work is based upon the general model described by Axelsson (1989). It is an isothermal model that consists of N capacitors, the i'th capacitor having capacitance κ_i. Each capacitor can be connected to up to N resistors describing the flow resistance between the capacitors and between any capacitor and an external pressure source.

The governing equation for mass flow is

$$Q_{ij} = S_{ij}\left(P_i - P_j\right) \qquad (1)$$

where Q_{ij} is the mass flow from the i'th capacitor to the j'th capacitor in kg/s, S_{ij} is the flow resistance between those capacitors in ms, and P_i and P_j are the pressure, measured in Pa, in capacitor i and j respectively. Note that $S_{ij} = S_{ji}$.

Pressure change is obtained from the equation describing conservation of mass

$$\mathrm{K}_i \frac{dP_i}{dT} = -\sum_{j=1}^{N} Q_{ij} - S_i\left(P_i - P_0\right) - F_i \qquad (2)$$

Here K_i is the capacitance of the i'th capacitor in ms^2, T denotes time, S_i is the flow resistance between the i'th capacitor and the external pressure source, and F_i is mass flow due to "pumping" from the i'th capacitor.

In our model we use three capacitors connected in series with an external pressure source. Fluid is pumped from the capacitor furthest removed from the external pressure source –this capacitor represents the region closest to the borehole. A schematic diagram of the model is shown in Figure 1.

As a further means of generalizing the model we use the following normalized variables:

$$\left|\begin{array}{ll} \sigma_{ij} = \dfrac{S_{ij}}{S_{21}} & \sigma_i = \dfrac{S_i}{S_{21}} \\ \kappa_i = \dfrac{\mathrm{K}_i}{\mathrm{K}_1} & t = \dfrac{S_{21}}{\mathrm{K}_1}T \\ f_1 = \dfrac{F_1}{S_{21}P_y} & p_i = \dfrac{P_i}{P_y} \end{array}\right. \qquad (3)$$

In equation (3) P_y denotes the initial value of P_3 which in our case is P_0.

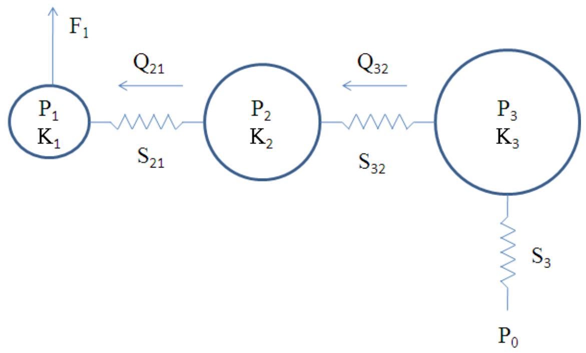

Figure 1: Schematic diagram of the lumped parameter model. P_0 represents an external pressure source and D_1 represents flow out of the system.

Combining (1) and (2) into a single, normalized equation with $\sigma_1 = \sigma_2 = \sigma_{31} = f_2 = f_3 = 0$ yields the governing equation for the system response:

$$\left(\frac{d}{dt}+\mathbf{M}\right)\begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} = \begin{bmatrix} -f_1/\kappa_1 \\ 0 \\ \frac{\sigma_3}{\kappa_3}p_0 \end{bmatrix} \tag{4}$$

$$\mathbf{M} = \begin{bmatrix} \frac{\sigma_{21}}{\kappa_1} & -\frac{\sigma_{21}}{\kappa_1} & 0 \\ \frac{-\sigma_{21}}{\kappa_2} & \frac{\sigma_{21}+\sigma_{23}}{\kappa_2} & \frac{-\sigma_{23}}{\kappa_2} \\ 0 & \frac{-\sigma_{23}}{\kappa_3} & \frac{\sigma_{23}+\sigma_3}{\kappa_3} \end{bmatrix}$$

Note that in equation (4) $\sigma_{21} = \kappa_1 = 1$ under most circumstances, although we do vary from those values when conducting a sensitivity analysis as will be discussed later. Also note that in the data presented in this paper we assume that the system is closed, i.e. σ_3 = o.

For given physical parameters and operation history, f_1, the system response is obtained using a fourth order Runge-Kutta algorithm. The physical parameters may either be predetermined or obtained empirically from production data in a manner similar to that described by Axelsson (1989).

2.2 Economics Model

We begin by looking at the equation that is used to describe discretized future propagation of demand for the time interval $t_1 \ldots t_N$:

$$d_k = d_0\left(1+C\sin(2\pi\omega t_k)\right)\ldots$$
$$\ldots\left(1+\frac{h}{t_N}t_k\right)\left(1+\frac{e}{\sqrt{N}}\sum_{m=1}^{N}\nu_m\left(0,s^2\right)\right) \tag{5}$$

Here d_k is the demand at time t_k, d_0 the initial demand, ω is the frequency of seasonal variations in demand, C the amplitude of those variations, h the trend in demand and $\nu_m(0,s^2)$ is a sampling from a normal distribution with mean 0 and variance s^2. Thus the last parenthesis on the right hand side of (5) introduces stochastic behavior into the demand. In accordance with equation (3), all of the mass flow variables are normalized by the factor $1/(S_{21}P_y)$ and the time related variables by the factor S_{21}/K_1.

Let us now turn our attention to the production side. The power needed to meet a given production rate, f_1, is given by

$$a = f_1\left(p_r - p_1\right) \tag{6}$$

Here a is the normalized power and p_r is a normalized reference pressure. The scaling factor for power is $\rho/(S_{12}P_y^2)$ where ρ is the density of the geothermal fluid. It is assumed that the producer operates a number of pumps of equal pumping power a_0. The production capacity, measured as normalized power, is thus

$$a_{max} = la_0 \tag{7}$$

Here, *l* is the number of pumps. It is assumed that production must meet demand with the following exceptions: Up to n consecutive days of demand exceeding production are allowed; up to m days per year of demand exceeding production are allowed; the production limit set by the *exergy ratio* must not be exceeded. Thus the operator has some flexibility to decide not to meet spikes in demand characterized by the parameters n and m.

The aforementioned exergy ratio is used to set the ultimate production limit of the field. It simply states that the energy needed to pump a mass unit of fluid from the well should not exceed a given fraction of the specific exergy of the fluid:

$$\beta \le \frac{xf_1}{a} = \frac{x}{p_r - p_1} \tag{8}$$

Here, a is the normalized power needed to pump the fluid, x its normalized specific exergy and b the normalized exergy ratio. Note that the scaling factor for specific exergy is ρ/P_y. Equation (8) may be recast to the minimum allowable pressure in the well represented by capacitor 1:

$$p_1 \ge p_r - \frac{x}{\beta} = p_{min} \tag{9}$$

Note that in our formulation the pressure decreases as the fluid level in the well drops. Thus equation (9) describes the lowest allowable fluid level.

It is now possible to summarize how the production rate is determined:

1) As long as $p_1 > p_{min}$ or $q_{12} > d$

$$f_1 = \min\left(d, \frac{a_{max}}{p_r - p_1}\right) \tag{10}$$

with the stipulation that the number of pumps must be increased sufficiently to meet demand, if demand exceeds supply for a period characterized by the parameters n and m described above.

2) for $p_1 \le p_{min}$ and $q_{12} < d$

$$f_1 = \left(p_2 - p_1\right)\sigma_{21} \tag{11}$$

Next we address costs and revenue for the operations. It is assumed that the fluid is sold at a price of C_w, measured in $/m^3, electricity for running the pumps is bought at a price of C_{el}, measured in $/kWh. Pumps are added at a price of C_p, measured in $. The corresponding normalized parameters are:

$$c_w = \frac{S_{12} P_y}{\rho C_p} C_w$$
$$c_{el} = \frac{S_{12} P_y^2}{3.6\times 10^6 \rho C_p} C_{el} \qquad (12)$$
$$c_p = 1$$

The present value of the profit of operations, ψ, is given by:

$$\psi = \sum_k \frac{c_w d_k - a_k c_{el} - l_q c_p}{(1+r)^{t_k}} \qquad (13)$$

In equation (13) a_k is the normalized pumping power at time t_k, r is the discount rate of the project, and l_k is the number of pumps added at time t_k.

Let us now remark on how the decision to add new pumps is implemented in the model. Since it can be complicated to introduce the decision to add pumps into the system equation itself, an iterative procedure is adopted: First a demand curve, d, for the time period t_1 … t_N is generated, and the system response to an extraction rate described by equation (10) calculated (or by equation (11) if applicable). Next the production curve, f_1, is compared to the demand curve and a time, t_q, found where demand has exceeded supply for the maximum allowable period, characterized by n and m. At this time the number of pumps is increased so that supply may meet demand. Using the same demand curve as was generated in the first step the iteration proceeds by determining a new flow rate determined from equation (10) or (11) beginning at time t_q. This is followed by calculation of the pressure response to the new production rate from t_q etc.

2.3 Model Implementation

The simulations that we run are repeated for 20,000 different manifestations of stochastically generated demand curves. These demand curves, along with criteria regarding sustainability and conditions on meeting demand, determine the production rate. Hence we are effectively simulating 20,000 different time-series for production per run. They are largely stochastic in nature, but production is also determined by the system response.

Finally, we look at the parameters used in the simulations in this paper. The parameters for the physical system are based on the Laugarnes reservoir in SW-Iceland and are adopted from Axelsson (1989). Parameters pertaining to production are presented in Table 1.

For the economics model we use the parameters given in Table 2.

Table 1: Production parameters. $P_{i|t=0}$ is the initial pressure in all capacitors. A_0 is the power capacity of individual pumps.

Parameter	Value	Units	Normalized
K_1	773	ms^2	1
K_2	2.09×10^4	ms^2	27
K_3	3.64×10^5	ms^2	471
S_{12}	3.68×10^{-4}	ms	1
S_{23}	6.18×10^{-4}	ms	1.679
$P_{i\|t=0}$	5	MPa	1
P_r	5	MPa	1
A_0	200	kW	2.12×10^{-2}

Table 2: Parameters for the economics model. D_0 is the initial demand. h, c and s are parameters used in equation (5). X is the specific exergy of the fluid.

Parameter	Value	Dimension	Normalized
D_0	130	kg/s	0.071
h	0, 5, 10		
C	0.5		
s	0.5		
X	36.122	kJ/kg	7.03
β	10		
C_w	0.824	$/m^3	9.585×10^{-7}
C_{el}	0.10	$/kWh	5.976×10^{-4}
C_p	1.625×10^6	$	1
r	15.15	%	

The initial demand is the average production rate from the Laugarnes field over the period from 1968 to 1982. The values for C_w, and C_{el}, are taken from price listings from Reykjavík Energy (Orkuveita Reykjavíkur) in 2008. The value for C_p is a cost for wells taken from Stefánsson (2002). The discount rate is taken to be the internal rate of return for the case when h = 0. This is the base value for the discount rate, but the effect of varying will be explored later. It should also be noted that the oscillatory term in equation (5) has a period of one year.

3. RESULTS

3.1 Production and System Response

It is instructive to examine how the system responds to a sample manifestation of the demand curve. Figure 2 shows the production rate over 50 years and how the pressure in the capacitors varies in response. Not surprisingly, the smallest and innermost capacitor shows the strongest reaction to production. We also see that after approximately 15 years of production the minimum well pressure set by the exergy ratio is reached. This leads to a decrease in production, since it is now limited by the flow rate from capacitor 2 to capacitor 1 which falls as the pressure in capacitor 2 drops. Note that the production curve is shifted horizontally to help distinguish it from the pressure curves. The scaling is unchanged though.

Figures 3 and 4 show the production curve of Figure 1 in more detail, as well as the production capacity. From Figure 3, it is clear how the production capacity is increased in response to increased demand. The spikes where production seemingly exceeds production capacity are numerical artifacts that stem from p_1 reaching the minimum set by the exergy ratio and recovering from it. They could be removed by iterating the system response once more for each point of recovery, but the computational effort is not justified by the negligible gain in accuracy.

Figure 4 shows a detail from Figure 3. If production were to follow demand, the peaks would be roughly sinusoidal. Since our model allows the producer not to meet demand for a number, n, of consecutive days, or for m days per year, the producer does not have to increase production capability immediately.

3.2 Statistical Analysis

The most useful aspect of our model is that because of its simplicity, it is possible to survey a large number and conduct a statistical analysis of the results. This gives the opportunity to estimate the likelihood of the profitability, longevity etc. of the field. As the economic analysis is dependent upon the discount rate, a measure of the cost of financing, we must decide upon sensible values for it. To do this we set the discount rate as the internal rate of return of the project, when there is no trend in demand and stochasticity (uncertainty) has been removed from the demand curve. The internal rate of return is the discount rate at which the net present value of operations is zero. This is a conservative value, as the project is expected to be more profitable when there is a positive trend in demand. Using these assumptions we find the internal rate of return to be 15.5%.

The statistical analysis is performed with 20,000 runs of randomly generated Wiener processes (see equation (5)) for the three different trend cases, h = 0, 5, 10. Other parameters are the same as in Tables 1 and 2. Figure 5 shows the probability density function (PDF) and cumulative distribution function (CDF) for the net present value of operations for the three different trend scenarios.

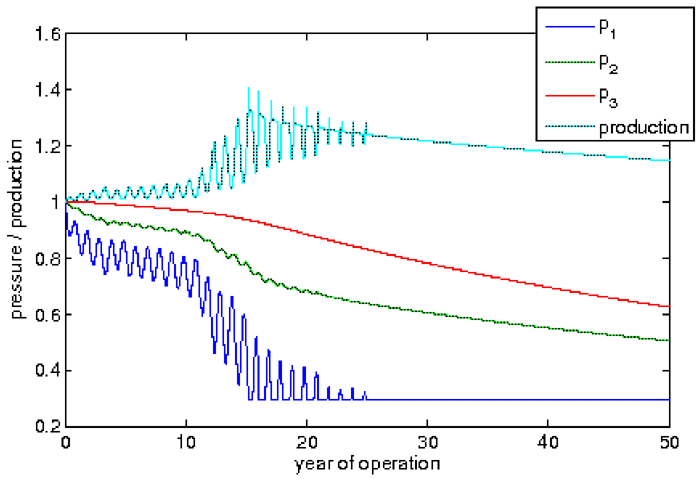

Figure 2: Typical response of the system to production.

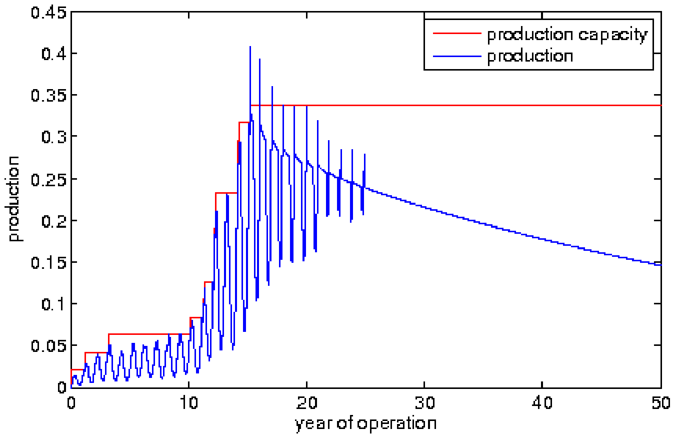

Figure 3: Production curve and production capacity.

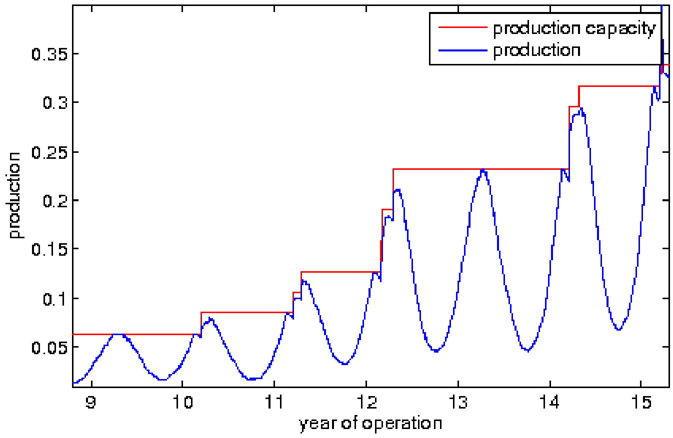

Figure 4: Detail from Figure 3 showing the allowed lag in meeting demand.

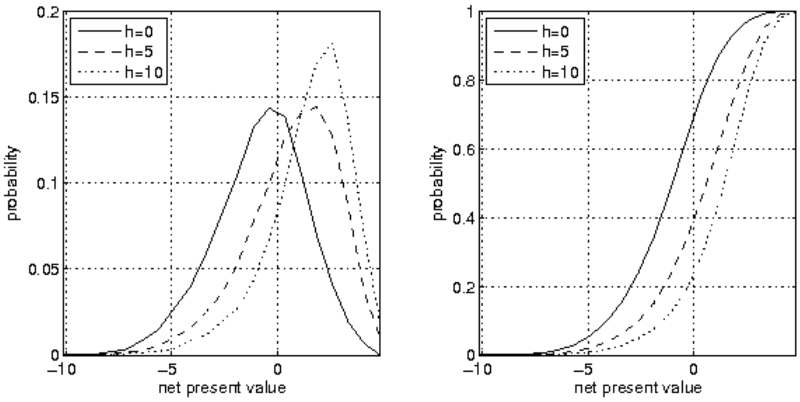

Figure 5: Statistical distribution of net present value. The graph on the left shows the probability density function, and the one on the right the cumulative distribution function.

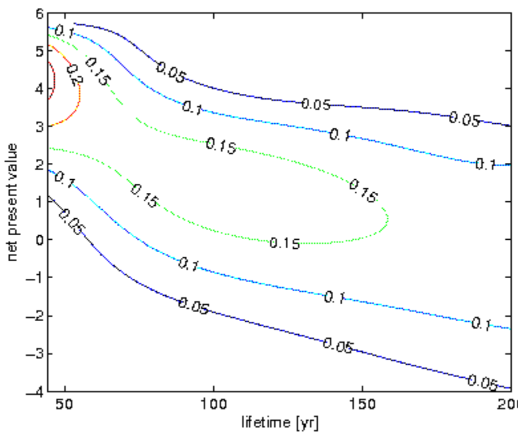

Figure 6: Two dimensional PDF as a function of net present value and lifetime. h = 0.

It is interesting to note that even though the discount rate was set using the IRR for the h = 0 case in the absence of stochastic effects, the greater mass (68.8%) of the PDF in the h = 0 case is in a region where the net present value is negative. In fact all of the distribution functions are skewed to the negative side. This is a manifestation of the cost of imperfect knowledge. The h = 5 and h = 10 cases are more profitable because more revenue is coming in at earlier stages. However the field may have a shorter lifetime under such aggressive production.

We define the lifetime of the field as the time that it takes for the pressure, p_1, to drop to the minimum value set by the exergy ratio. In Figure 6, we have mapped out the contours of the PDF for h = 0 as a function of net present value and lifetime. This is done by using the results from the 2000 runs to construct a 20×20 histogram with respect to these variables. They are then run through a Chebyshev filter and interpolated onto a 200×200 grid using cubic interpolation.

From Figure 6 it is apparent that the more aggressive production that corresponds to a shorter lifetime leads to a higher net present value, due to the time value of money. It also leads to a lesser variance in the PDF. This may be compared to the case where h = 10, shown in Figure 7. There we see that increasing the production rate with time offsets the time value of money effects that led to a decrease in the net present value with lifetime in the previous case. However the variance in the PDF still increases with lifetime.

One of the factors that need to b e addressed is the effect of uncertainty in demand on the profitability of the project. This uncertainty is measured by the variance of the Wiener process. Figure 8 shows the effects of uncertainty on present value in the case of h = 0. As was expected, greater uncertainty about demand broadens the PDF. Interestingly the peak of the PDF does not seem to be strongly affected.

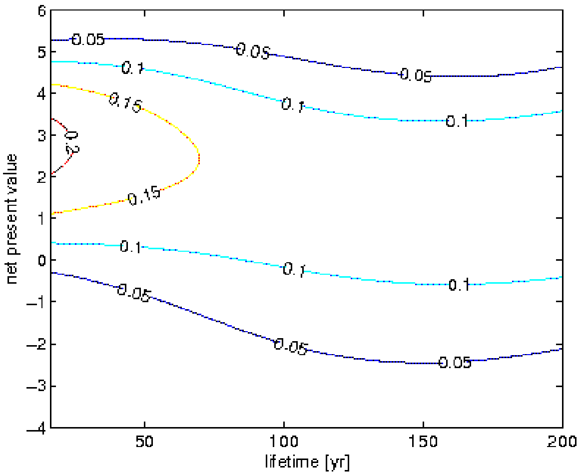

Figure 7: Two dimensional PDF as a function of net present value and lifetime. h = 10.

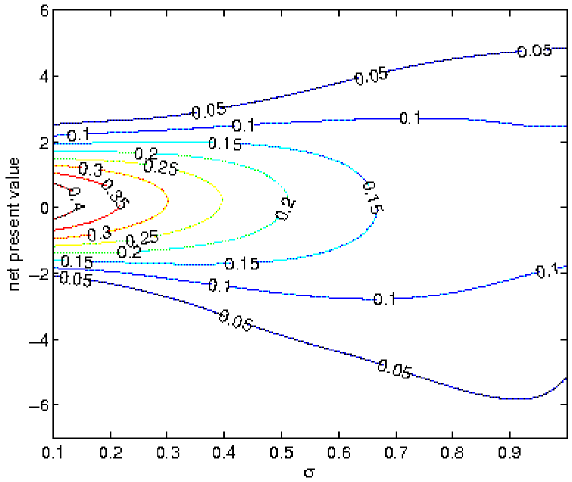

Figure 8: Two dimensional PDF as a function of net present value and variance of the Wiener process. h = 0.

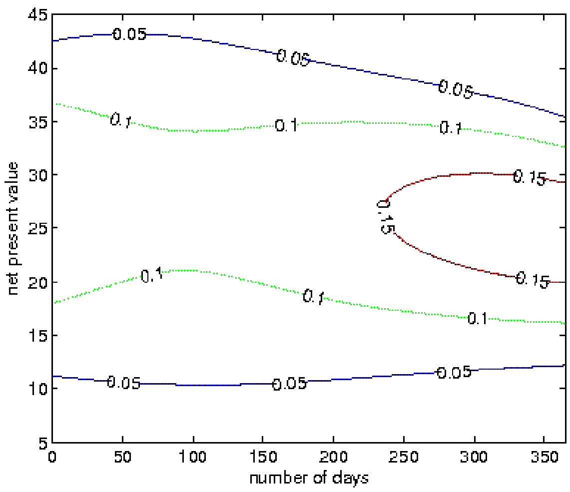

Figure 9: Two dimensional PDF as a function of net present value and waiting period. r = 5% and h = 0.

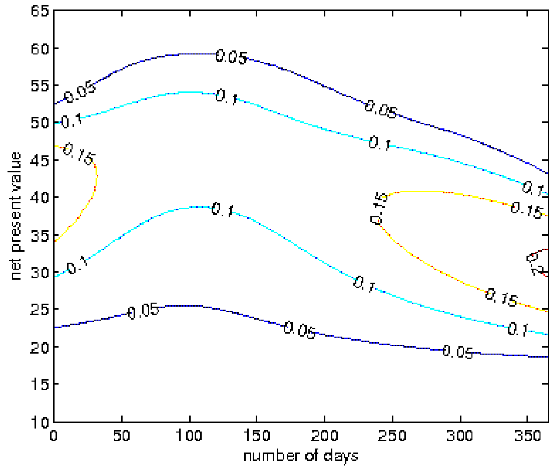

Figure 10: Two dimensional PDF as a function of net present value and waiting period. r = 5% and h = 5.

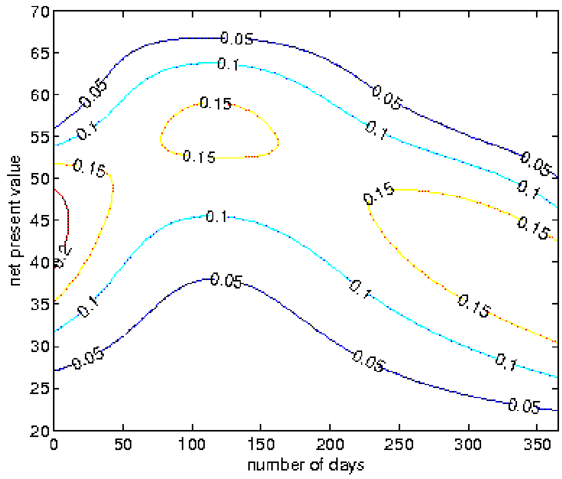

Figure 11: Two dimensional PDF as a function of net present value and waiting period. r = 5% and h = 10.

3.3 Optimal Waiting Period

In our model we make the assumption that the producer has to meet demand, but is allowed some waiting period before increasing production capacity to do so. This means that the producer is not forced to incur costs to meet sporadic demand spikes. We are interested in investigating the effect of the allowable waiting period between demand exceeding capacity and the time when capacity is increased. The question also arises whether there is some optimal waiting period. To glean some information regarding this, we run a series of simulations with varying waiting periods. The demand is allowed to exceed production for n consecutive days or for m = 2×n per year. We then analyze the PDF functions for the discount rates r = 5% and r = 15.15%. As before we examine three scenarios for the trend in demand, h = 0, h = 5 and h = 10.

Figures 9 – 11 show the PDF's as a function of waiting period, n, and net present value for a discount rate of r = 5% and trends of h = 0, h = 5 and h = 10 respectively.

From Figures 9 – 11 it can be seen that the location of the peak of the PDF is negligibly affected when there is no trend in demand. However, when a trend in demand is present there is a clear optimal waiting period, slightly over

100 days. The explanation for this is that, if there is no trend, it is of course most profitable to supply the demand at all times with a simple seasonal variation. When there is a trend in demand, it seems that waiting out seasonal peaks is profitable, until the trend in demand justifies an increase in production capacity. This effect becomes more pronounced with increased values of h.

3.4 Sensitivity Analysis

We have conducted a sensitivity analysis for the physical parameters κ and σ, in terms of field lifetime and net present value of operations. The results of these are shown in Figures 12 and 13. Not surprisingly both lifetime and profitability are most sensitive to the permeability of the system (σ_{12} and σ_{23}) and the capacity of its largest component (κ_3). In particular it is the permeability closest to the well that is of greatest importance.

3.5 Periodic Production

One question that arises upon occasion is whether it might be more profitable to operate a field aggressively for some duration, followed by a period of decreased or no production while the field recuperates. We have conducted some preliminary investigations into this. We assume that the producer has a pumping capacity of 2MW (corresponding to 10 pumps or wells) and access to an unlimited market. We look at the effects of periodic pumping on the state of the reservoir and the net present value of operations. Figure 14 shows the response of the system to production with a period of 40 years.

The smaller capacitors regenerate quickly when pumping ceases. The pressure in the largest capacitor does not recuperate, since the system is closed.

We next mapped out the net present value as a function of pumping period and pumping capacity. The results are shown in Figure 15. From this figure it becomes apparent that continuous production is more profitable than periodic production, although there is a minimum when the period is approximately 5 years. That minimum is especially pronounced for large production capacity. This indicates that it might be profitable to conduct very short period intensive pumping, if the producer is not bound to meet long term demand.

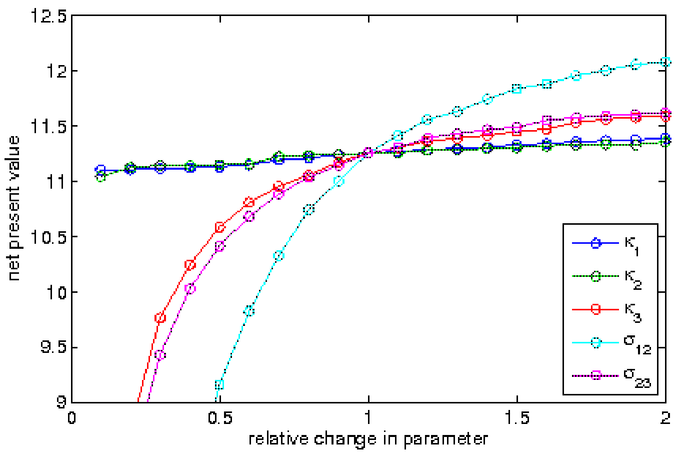

Figure 12: Sensitivity of net present value to the physical parameters of the system. h = 5 and r = 15.15%

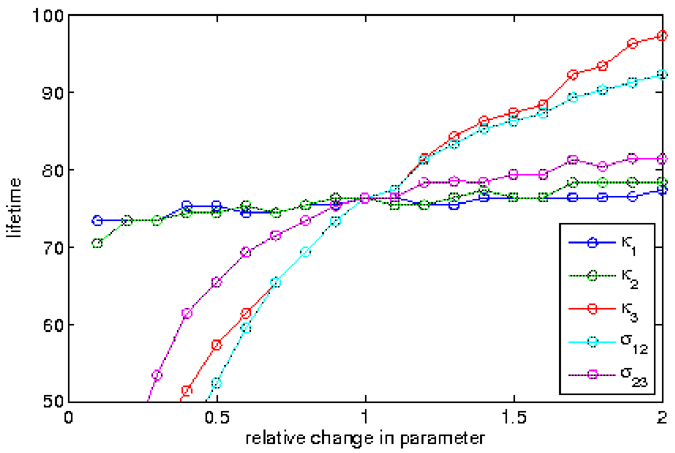

Figure 13: Sensitivity of lifetime to the physical parameters of the system. h = 5 and r = 15.15%

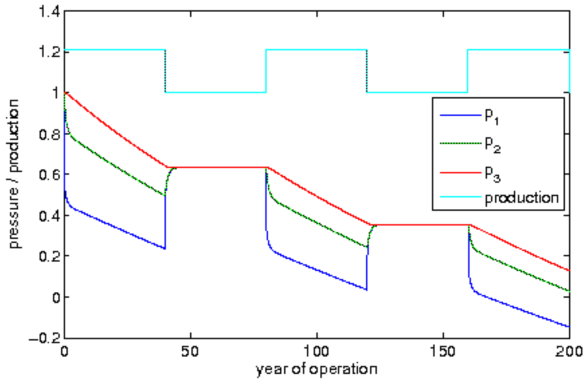

Figure 14: Response of the system to periodic pumping with a 40 year period. r = 15.15%.

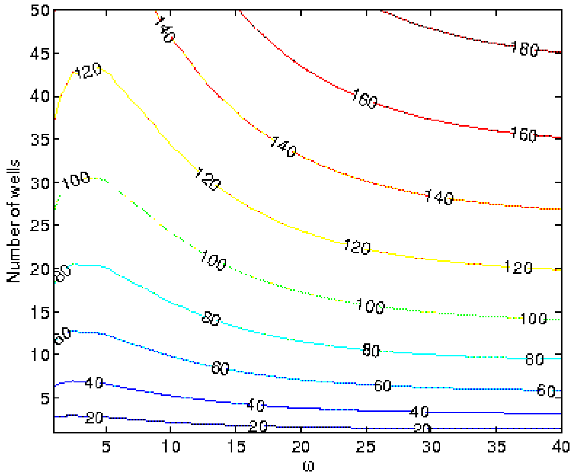

Figure 15: Contours of net present value of the operation with respect to pumping capacity and production period, ω.

3. CONCLUSION

We have used lumped parameter models, which have been shown to produce adequate models of low temperature geothermal systems, as a basis for doing wide ranging parametric analysis of operations with regard to profitability and lifetime. This analysis may include stochastic effects. We have also introduced a quantitative measure of sustainability into the model in the form of the exergy ratio, which limits the amount of power used for retrieving the fluid to a set fraction of the exergy of the fluid.

We then carry out some analysis using the assumption that the producer is bound to meet demand until the well pressure drops to a minimum value set by the exergy ratio. We find that, due to the time value of money, higher exploitation rates are more profitable though the lifetime of the field is decreased.

We also examine the case where the producer is permitted not to meet demand for n consecutive days or at most 2×n days per year. We look to see whether there is an optimal waiting period, in terms of profitability, between production being exceeded by demand and increasing production capacity. If there is no long term trend in demand, this is not the case. However, if there is a trend in demand, such an optimum does exist and becomes more apparent with increasing trend in demand.

Finally we have carried out a rudimentary examination of periodic production for an unlimited market. The results of which indicate that continuous production is more profitable than periodic production, except in the case of short term periods (< 5 years) with very intense production.

Although the simulations that we have conducted are based upon very simple models, it has value in surveying a broad parameter range and giving a measure of risk and uncertainty. There are some obvious limitations to the model that we use. For instance there is the question of increasing capacity. In our cost analysis we have priced this as if an extra well were added. In terms of the physical model, we treat this more as adding another pump. Adding a well would most likely be more accurately modeled by adding another small capacitor to the system. That would probably alter the lifetime of the field quite a bit as the water level of the well would not drop as rapidly. The economic model is especially rudimentary, and improvement thereupon is likely to yield some useful results. For instance more realistic demand curves and pricing would improve upon the model

We are currently extending this work to include: optimization calculations; different market scenarios; better performance measures than net present value; and possible high-temperature applications.

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